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Karst conduits formed along fracture corridors in anticline hinges of carbonate units: implications for reservoir quality

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Summary

The hypogenic caves developed in carbonate units have a significant structural control but most of their features are not detect by conventional methods due to their size below seismic resolution. This contribution focuses on the structural, petrographic and geometric characterization of karst conduits in Neoproterozoic carbonates of the Salitre Formation, central part of São Francisco Craton, Brazil. We address the influence of fractures and folds on the development of karst conduits through field and laboratory analysis and the application of Light Detection Ranging to characterize cave/conduit geometry. The preliminary results indicate that the process of karstification are intensified in fractures corridors developed along fold hinges, which create fluid flow corridors in carbonate units and may change petrophysical reservoir properties.

Introduction

Carbonates rocks affected by natural fractures form significant hydrocarbon and groundwater reservoirs. Karst systems are form where dissolution of rocks by aqueous fluid is the dominant process (De Waele et al., 2009) and are related to the storage and entrapment of hydrocarbons and groundwater (Xu et al., 2017). Karst features are controlled by structural heterogeneities, such as faults and fractures, which influence fluid flow, provide preferential pathways for geofluids with the development of secondary porosity, and could influence the production and exploitation of oil reservoirs (Frumkin, 2013; Klimchouk et al., 2017; Ogata et al., 2012).

Karsts could be classified as hypogenic and epigenic, according to their recharge flow. Normally hypogenic karst occurs at varying depths from shallow subsurface to several kilometers, formed by ascending fluids, whereas epigenic karst occurs with downward fluid flow (Klimchouk, 2009). Hypogenic karst distribution may vary over time, according to mechanisms that control their development, such as chemical dissolution and hydrothermalism (Auler and Smart, 2003; De Waele et al., 2009; Ennes-Silva et al., 2016). Beyond the recent advances on the knowledge about karst, several parameters such as evolution, structural control, geometry and karst influence on carbonate reservoirs have not been fully clarified through conventional exploration techniques such as seismic surveys, because they are often smaller below seismic resolution, or by well data, because they present high complexity and larger size for the application of this method (Cazarin et al., 2019). Karst systems can cause problems such as loss of fluid circulation and well collapse in exploited oil field (Xu et al., 2017). On the other hand, karst can significantly enhance fluid flow in carbonate reservoirs (Pantou, 2014). Hence, the use of outcrop analogues (Giuffrida et al., 2019; La Bruna et al., 2018) represent the main approach to minimize errors and allow a reliable reservoir reconstruction.

This contribution focuses on the analyses of fracture corridors at the scale of less than 1 km and their relations with folds in hypogenic karst systems. This study was performed in the Salitre Formation, a carbonate reservoir analogue with high occurrence of hypogenic karst systems, which is part of an extensive Neoproterozoic platform with sedimentation initiated during the transgression of an epicontinental sea over much of the São Francisco Craton and adjacent areas, central Brazil (Misi and Kyle, 1994; Cazarin et al., 2019).

Method

This contribution included field and laboratory analysis. The structural data were measured inside and outside four caves in the Irecê Basin to understand the relationship between both background and fault related deformation, which led to karst conduit nucleation. We measured data of fractures, beddings, fold hinges, and faults. Away from the major fault zones, fractures are stratabound and non-stratabound. Differently, the fault damage zones are mainly composed of non stratabound fractures. The laboratory procedures consisted of petrographic analysis of thin sections carried out using a polarized light microscope. The carbonate units were classified according to the classification of Dunham (1962) to describe the composition of the different layers affected by karstification.

Furthermore, Light Detection and Ranging (LiDAR) data were acquired with mobile LiDAR ZEB-Revo from GeoSLAM. The mobile lidar captures raw laser ranging measurements and inertial data to generate real-time point clouds while the operator is moving through the cave terrain. The equipment comprises a laser range scanner coupled to an inertial measurement unit (IMU) mounted on a rotating drive, which produces the third dimension during the rotation.

The device uses a 3D SLAM algorithm to fuse the 2D laser scan data with the IMU data to generate the 3D point clouds (Islam, 2019). These point clouds were processed by the CloudCompare software version 2.11 with the filter Eye-dome Lighting that enhances the visualization of the cave geometry.

Preliminary results

We carried out a structural analysis of the four caves (Figure 1) in most representative zones. Were measured 383 sedimentary bedding on both sides of the conduits, 137 (non-stratabound and stratabound fractures inside the caves and 109 in the outside part. The stereoplot of sedimentary bedding shows gentle folds, with dip varying between 5º to 20º (Figure 2 a, b), predominantly forming anticline folds. The fractures inside the caves are concentrated in the central part of conduits and spaced fractures occur away from fold hinges. In some points of the caves, the observation of fractures in the top of de galleries is difficulty due to high dissolution (Figure 2 c, d), which is still active in several zones.

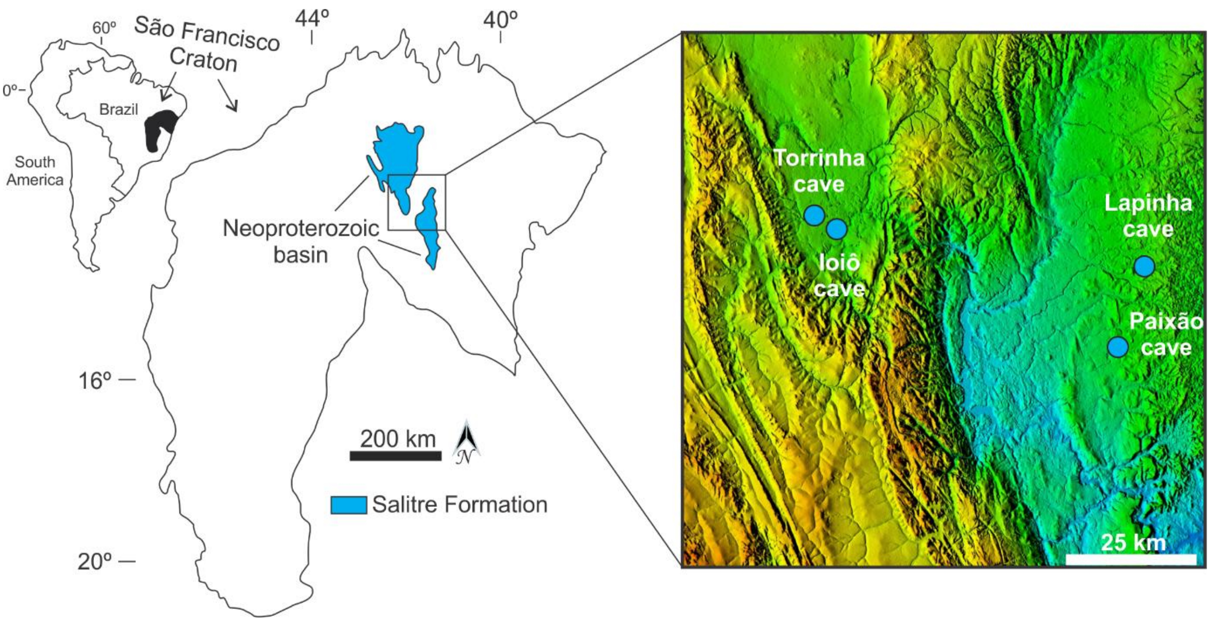

Figure 1: *Location of the study Neoprotezoic basins in the São Francisco Craton and Shuttle radar topography (SRTM) image showing the study caves.*

The application of high-resolution LiDAR imagery, together with structural data, allowed the description of zones of high dissolution (Figure 2). These zones are in the central part of the ceiling of the cave conduits, marked by a concentration of fractures (fracture corridors). These high-dissolution zones occur in anticline hinges, which exhibit gentle geometry with 10º dip of limbs. These fold hinges are marked by high concentration of fractures. The geometry of the conduits has a rectilinear and/or maze pattern, sometimes with an en-echelon geometry with orthogonal links along fractures between parallel conduits. The general geometry of the conduits along anticline hinges present an approximately horizontal ellipsoidal shape. Besides folds and fractures, faults could influence the petrophysical properties of rocks in the cave, increasing for example the secondary porosity due to the higher deformation rate in the fault core. The background deformation exhibit the same pattern inside and outside the caves (Figure 3) and it influenced the formation of the cave conduits.

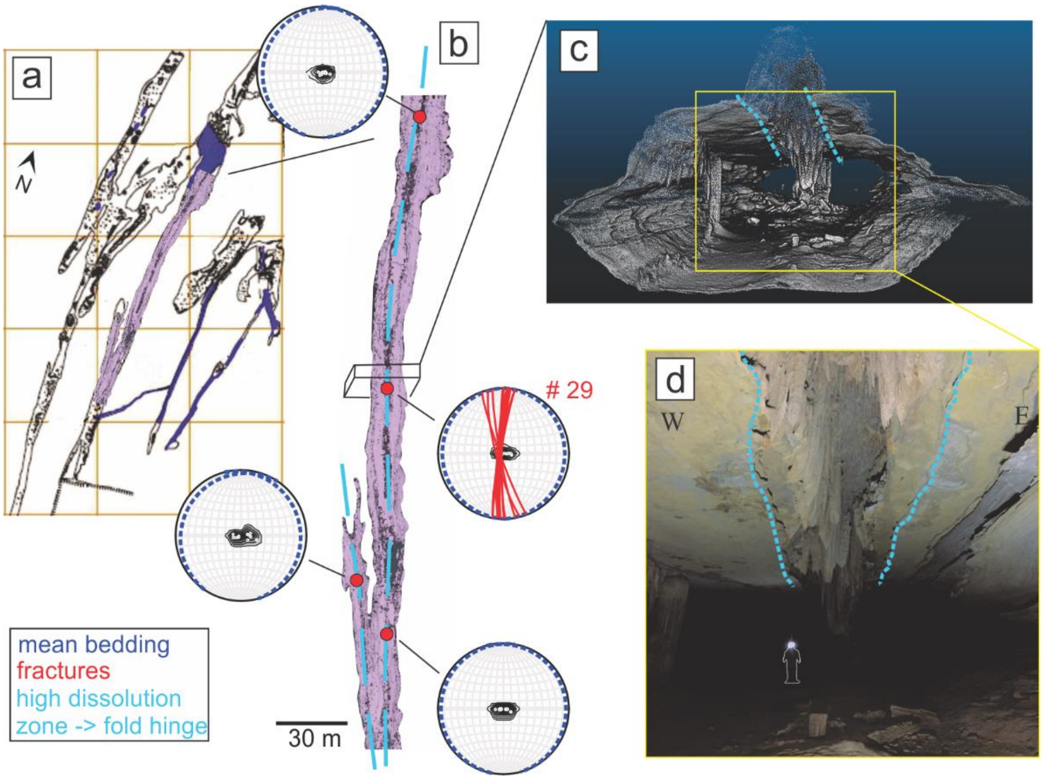

Figure 2: ***(a)*** *map of Ioiô cave with passage geometry derived from LiDAR acquisition;* ***(b)*** *LiDAR data with equal area projection showing mean bedding (blue), poles of the beddings, fractures (red) and high dissolution zone (dashed blue line);* ***(c)*** *Slice of LiDAR data showing the ellipsoidal shape and zone of high dissolution and;* ***(d)*** *picture of the exactly position of slice C.*

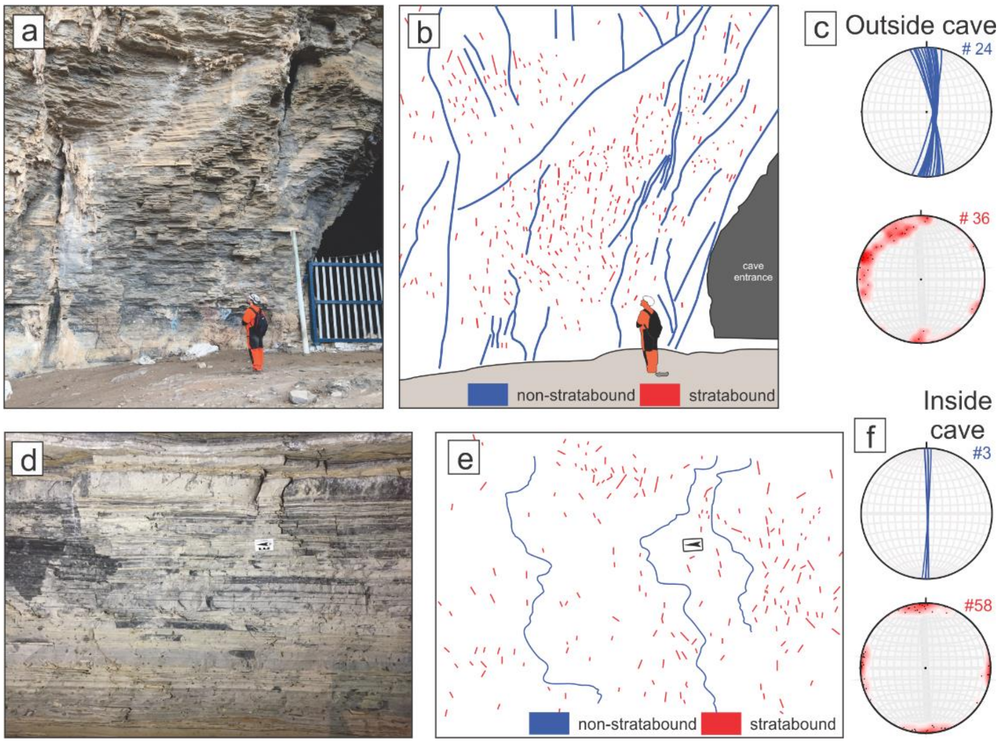

Figure 3: ***(a)*** *outsite part of Lapinha cave;* ***(b)*** *linedrawing of the outside part;* ***(c)*** *equal area projection of non-stratabound and poles of stratabound fractures;* ***(d)*** *N-S-oriented wall in cave conduit;* ***(e)*** *linedrawing of (d)* ***(f)*** *equal area projection of non-stratabound and poles of stratabound fractures that affected the cave.*

We propose a preliminary scheme for the formation of conduits along fracture corridors at anticline hinges based on data of previous studies in the region and from our study (Figure 4). The Neoproterozoic carbonate units of the Salitre Formation were deformed by a compressive tectonic regime marked by folds and thrusts generated in late Brasiliano orogeny (630-575 Ma). This compressive regime provided fractures that are concentrated along fold hinges and acted as pathways for the ascending fluid flow (Figure 2). The karstification process started when hypogenic fluids affected carbonate units and caused dissolution. The process intensified in carbonate layers marked by absent of stylolites. Dissolution was less intense in siliciclastic layers such as siltstones or syn-sedimentary breccia. These units with a significant siliclastic content and high number of stylolites acted as seal for the ascending fluid flow. The sealing layers induced horizontal fluid flow and dissolution in the underlying carbonate layers (Figure 4).

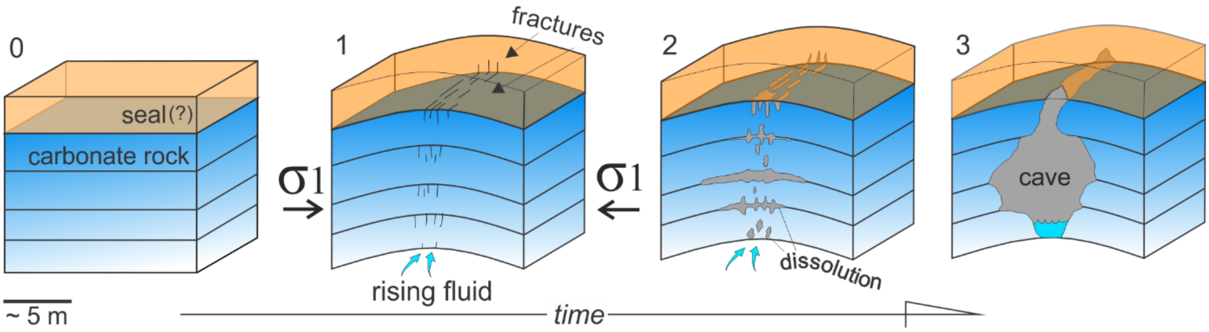

Figure 4: *Time evolutionary model proposed for development of the hypogenic conduits in carbonate units of the Salitre Formation, Brazil.*

The results presented in this study contribute to the characterization of hypogenic cave conduits that may act as flow corridors in carbonate reservoirs. The geometry of these caves exhibits rectilinear or maze patterns, which usually have a horizontal ellipsoid shape. The presence of fractures, concentrated in fold hinge, facilitated fluid circulation and improved the process of dissolution, creating high dissolution zones.

References

Auler, A.S., Smart, P.L., 2003. The influence of bedrock-derived acidity in the development of surface and underground karst: Evidence from the Precambrian carbonates of semi-arid northeastern Brazil. Earth Surf. Process. Landforms 28, 157–168. https://doi.org/10.1002/esp.443

Cazarin, C.L., Bezerra, F.H.R., Borghi, L., Santos, R. V., Favoreto, J., Brod, J.A., Auler, A.S., Srivastava, N.K., 2019. The conduit-seal system of hypogene karst in Neoproterozoic carbonates in northeastern Brazil. Mar. Pet. Geol. 101, 90–107. https://doi.org/10.1016/j.marpetgeo.2018.11.046

De Waele, J., Plan, L., Audra, P., 2009. Recent developments in surface and subsurface karst geomorphology: An introduction. Geomorphology 106, 1–8. https://doi.org/10.1016/j.geomorph.2008.09.023

Ennes-Silva, R.A., Bezerra, F.H.R., Nogueira, F.C.C., Balsamo, F., Klimchouk, A., Cazarin, C.L., Auler, A.S., 2016. Superposed folding and associated fracturing influence hypogene karst development in Neoproterozoic carbonates, São Francisco Craton, Brazil. Tectonophysics 666, 244–259. https://doi.org/10.1016/j.tecto.2015.11.006

Frumkin, A., 2013. New Developments of Karst Geomorphology Concepts. Treatise Geomorphol. 6, 1–13. https://doi.org/10.1016/B978-0-12-374739-6.00112-3

Giuffrida, A., La Bruna, V., Castelluccio, P., Panza, E., Rustichelli, A., Tondi, E., Giorgioni, M., Agosta, F., 2019. Fracture simulation parameters of fractured reservoirs: Analogy with outcropping carbonates of the Inner Apulian Platform, southern Italy. J. Struct. Geol. 123, 18–41. https://doi.org/10.1016/j.jsg.2019.02.007

Islam, H.D., 2019. Geometry and Stability Analysis of Caves in Bahia , Brazil. Delft University of Technology.

Klimchouk, A., 2009. Morphogenesis of hypogenic caves. Geomorphology 106, 100–117. https://doi.org/10.1016/j.geomorph.2008.09.013

Klimchouk, A., Auler, A.S., Bezerra, F.H.R., Cazarin, C.L., Balsamo, F., Dublyansky, Y., 2016. Hypogenic origin, geologic controls and functional organization of a giant cave system in Precambrian carbonates, Brazil. Geomorphology 253, 385–405. https://doi.org/10.1016/j.geomorph.2015.11.002

Klimchouk, A., Palmer, A.N., De Waele, J., Auler, A.S., Audra, P., 2017. Hypogene Karst Regions and Caves of the World, Cave and Karst Systems of the World. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-319-53348-3

La Bruna, V., Agosta, F., Lamarche, J., Viseur, S., Prosser, G., 2018. Fault growth mechanisms and scaling properties in foreland basin system: The case study of Monte Alpi, Southern Apennines, Italy. J. Struct. Geol. 116, 94–113. https://doi.org/10.1016/j.jsg.2018.08.009

Misi, A., Kyle, J.R., 1994. Upper proterozoic carbonate stratigraphy, diagenesis, and stromatolitic phosphorite formation, Irece Basin, Bahia, Brazil. J. Sediment. Res. Vol. 64A, 299–310. https://doi.org/10.1306/d4267d84-2b26-11d7-8648000102c1865d

Ogata, K., Senger, K., Braathen, A., Tveranger, J., Olaussen, S., 2012. The importance of natural fractures in a tight reservoir for potential CO 2 storage: a case study of the upper Triassic–middle Jurassic Kapp Toscana Group (Spitsbergen, Arctic Norway) . Geol. Soc. London, Spec. Publ. 374, 395–415. https://doi.org/10.1144/sp374.9

Pantou, I., 2014. Impact of stratigraphic heterogeneity on hydrocarbon recovery in carbonate reservoirs: Effect of karst. Imperial College London.

Xu, X., Chen, Q., Chu, C., Li, G., 2017. Tectonic evolution and paleokarstification of carbonate rocks in the Paleozoic Tarim Basin. Carbonates and Evaporites 32, 487–496. https://doi.org/10.1007/s13146-016-0307-4